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Systems Study of Drilling for Installation of Geothermal Heat Pumps

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SYSTEMS STUDY OF DRILLING FOR INSTALLATION OF GEOTHERMAL HEAT PUMPS

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ABSTRACT

Geothermal, or ground-source, heat pumps (GHP) are much more efficient than air-source units such as conventional air conditioners. A major obstacle to their use is the relatively high initial cost of installing the heat-exchange loops into the ground. In an effort to identify drivers which influence installation cost, a number of site visits were made during 1996 to assess the state-of-the-art in drilling for GHP loop installation.

As an aid to quantifying the effect of various drilling-process improvements, we constructed a spread-sheet based on estimated time and material costs for all the activities required in a typical loop-field installation. By substituting different (improved) values into specific activity costs, the effect on total project costs can be easily seen.

This report contains brief descriptions of the site visits, key points learned during the visits, copies of the spread-sheet, recommendations for further work, and sample results from sensitivity analysis using the spread-sheet.

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I. INTRODUCTION

Ground-source, or geothermal, heat pumps (GHPs) use the earth as a large thermal reservoir from which heat can be extracted to heat a building, or to which heat can be deposited to cool that building. Heat is exchanged between the building and the earth by circulating a liquid through a freon-to-liquid heat exchanger on a reversing heat pump/air conditioning system. The circulation liquid exchanges heat between the heat pump and the nearby deep ground. Because the deep ground temperature is very moderate (50 to 70^{o}F) and nearly constant year round, GHPs enjoy improved efficiency relative to conventional heat pumps which exchange heat with outside air. Although GHPs are less expensive to operate than conventional alternatives (GHPs use 20-40% less energy than conventional air conditioners and about 1/3 the energy of resistance heaters), there is a major obstacle to their wider use. That is the high cost of the ground heat exchanger, which can be as much as half the total system installed cost.

The heat exchange between the heat pump and the ground may be effected with a variety of methods[1]. Some systems simply pass pumped groundwater from a well or other source through the heat pump and discharge the heated or cooled liquid to the surface or an injection well. More common are closed loop systems which use recirculated liquid (usually a water/alcohol mixture) passing through a buried loop of pipe in physical contact with the geological formation. The loop can be vertical, horizontal, or coiled in a spiral in a trench. This report will focus on vertical ground-source systems, where the open loop source or closed loop excavation consists of a vertical borehole.

The Geothermal Research Department at Sandia has a long history of working closely with the geothermal, oil and gas, and environmental drilling industries, and part of that work has been systems studies of drilling cost for high-temperature (power-plant) geothermal drilling. Based on this experience, DOE tasked Sandia to do a systems study of GHP drilling and loop installation. The objective of this study was to identify parts of the process, especially the drilling, where new or improved technology could have a significant impact to lower installation cost, and thus to lower market resistance for GHP. This report documents the results of that study.

II. METHODOLOGY

We can identify several different ways in which installation cost can be lowered:

1. Develop new technology which reduces the time spent on some part of the installation process.
2. Develop new installation equipment (drill rigs, etc.) which has a lower capital cost to the contractor.
3. Find new or substitute materials which are cheaper than those now used for installations.
4. Find ways to use less material than in current practice.
5. Introduce fundamentally different ways of doing installations, which lower cost by some combination of the methods above.

Once a way is found to lower the cost of some component of the installation process, the effect of that cost reduction must be evaluated for its importance to the overall project cost. In short, does the effect on total project cost justify spending money on technology development? As an example, increasing rate-of-penetration (ROP) is considered something of a Holy Grail in all types of drilling, but an increase becomes less important as the baseline ROP goes up. If a driller is already making 150-200 feet/hour (which was commonly observed in the site visits), then increasing the ROP to 250-300 feet/hour has a relatively small effect on the total project cost. On the other hand, if there is a hard formation or some other problem which limits ROP to 40 feet/hour, then increasing penetration rate to 70-80 feet/hour gives a significant cost savings. (See further discussion of this point on page 15.)

Attempts to identify and quantify areas of possible improvement in drilling took the form of site visits to approximately 12 different contractors doing loop-field installations. At each site several loop insertions were observed and detailed time records were kept for the activities required to complete the loop field. These performance figures were used to generate a spread-sheet in *MS Excel* format which has "typical" times and costs for loop installations and which can be used to easily evaluate the effect on total project cost of changing any performance time or material cost.

III. SITE VISITS

This section gives detailed descriptions of drilling operations at eight sites. The authors tried to collect consistent and comparable data at all the sites, so direct comparisons could be made among drilling techniques, geographical regions, and formations being drilled.

III-a. Fort Polk

The U. S. Army base at Fort Polk, Louisiana is the site of the largest GHP installation in the nation, possibly in the world. Over 4,000 dwellings, mostly duplex and triplex apartments but some single-family houses, were equipped with GHP units which required drilling a total of more than 9,100 holes. About a dozen drilling contractors were used for this project and it was not unusual for 12-15 rigs (representing 8-10 contractors) to be drilling at once. Not surprisingly, performance varied among contractors but, near the end of the project, better drillers were averaging 4-5 holes per day.

Figure 1 - Drill Rig at Fort Polk

Two site visits were made to Fort Polk, one near the beginning of drilling, the other near the end. Comparison of observations made during these visits showed that the drillers had advanced well up the learning curve during the course of the project. The most important lesson learned was that early problems with inserting loops into holes was primarily a function of drilling the holes too fast to allow proper cleaning (removing the cuttings from the holes as they were drilled.) The formation at Fort Polk contains a high percentage of clay, and failure to circulate all the drilled clay out of the hole usually resulted in a plug which prevented loop insertion. There were also significant improvements in logistics -- hauling away cuttings, grouting, header installation, etc. -- but it is important to recognize the near-uniqueness of a situation in which a very large number of holes in an almost uniform soil gives an opportunity to optimize installation for that setting. Although regional similarities certainly exist (and often make a GHP market possible) contractors generally face a new and different challenge with each job.

There were four basic activities in the Fort Polk project, each with its own equipment and crew: (1) drilling hole and installing loop, (2) grouting, (3) installing headers on loops and trenching to house, and (4) installing heat pump unit in dwelling. The strategy at Fort Polk was to let the drillers and header crews work well ahead of the heat pump installers, maintaining a backlog of installed loops, and then run 20 home installations/day. Although different people did different parts of the procedure below, this was the basic operation at Fort Polk, and is representative of nearly all the sites visited (see Figure 1, showing a typical drill rig at Fort Polk):

1. Locate utility lines.
2. Mark hole locations.
3. Move rig onto location, usually with a 3-man crew.
4. Set down mud pan (a small tank around the top of the hole; the drill string passes through it and the circulated mud with cuttings returns into it), mix small amount (~10-15 gal) of mud, using mix water from water truck or house. Some drillers use liquid EZ-Mud, which is quick but expensive; others use regular bentonite, some don't use anything (depend on native clay for viscosity).
5. Drill hole, shoveling cuttings out of mud pan as hole advances. Hole size ~ 4-1/4". Makeup water as above. Chips go into garbage cans or metal fork-liftable containers. Drill slowly enough to clean hole.
6. Make up or pick up heat exchanger loop (1" SDR-11 HDPE pipe) and pre-fill loop with water. Tape a piece of 1/2" re-bar (about 3' long) to the bottom of the loop, leaving the upper 2' of the bar untaped.
7. Circulate hole clean.
8. Pull drill string out of hole. Put drill pipe in rack on rig or ground, or on pipe truck.
9. Pick up ballast-weight bar on drill rig's wireline and fit the weight-bar socket over free end of re-bar on lower end of loop.
10. Feed loop into hole, paying out wireline to weight bar as loop advances. Work and push loop through tight spots. If loop will not go, pull it out of the hole and ream hole with drill string.
11. Pull weight bar out of hole.
12. Stake the top of the loop to prevent it floating out of hole.
13. Pump off remaining mud to waste container or to vacuum truck.
14. Clean and pick up mud pan.
15. Move chip container, chips, and waste mud tank to disposal site.

16. Rig down and move to next location.
17. Pump/install grout cap in loop hole or grout complete hole.
18. Dig trench (typical 36" deep) from well to building.
19. Install headers (HDPE fusion welded) on loop pipes.
20. Lay loop headers into trenches.
21. Fill trenches and restore; plant grass seed, etc.
22. File as-built drawings of wells and trenches with state or other regulatory agencies.
23. At a later time, install heat pump unit in dwelling and connect to loop-field.

There were a number of common problems at Fort Polk, all of which were, to some degree, site specific. That is, even though these problems could occur elsewhere (and probably have), almost all are related to either the drilled formation or the surface topography. These problems include the following:

1. Swelling clays and "booting" -- clays build up in wellbore and block mud return because of inadequate hole cleaning (either drilling too fast or insufficient circulation.)
2. Handling cuttings from many drills in the same vicinity was inefficient. (Cuttings and waste mud = ~ 1 cu yd per 200' well.)
3. Lost circulation in sandy intervals.
4. Communication between holes (pump into one hole while drilling, mud comes out a completed hole. This is probably related to the same sandy intervals causing lost circulation.)
5. Hole bridges, or partially caves in, before loop installation.
6. Some rigs and/or drillers are careless and destructive to yards and landscaping.
7. Hilly terrain makes rig set-up difficult.
8. Existing utility lines (underground and overhead) limit the possible hole locations.

Solutions to all these problems are possible and, indeed, many were developed during this project, and none of the solutions involved extensive technology development. There are generic problems which need advanced technology, but that is discussed in more detail in Section V, "Conclusions and Recommendations." In general, the Fort Polk project benefited from enormous economies of scale and had, well before the end of drilling, advanced far up the learning curve. It may be that early identification of some problems would have presented an opportunity for cost reduction by technology development, but this did not seem to be true later in the drilling.

III-b. Bertram Drilling

This project involved installation of 56 GHP loops in an area which would become the parking lot behind an office building in Ogden, Utah. Bertram Drilling is a fairly large company, with ~ 10 rigs in the U.S., and this drill is from Billings, Montana. This drill stays busy; the driller says it had worked 13.5 out of the last 16 months. Bertram was contracted by Earth Energy Technology, another Billings company which provides GHP design and consultation. EET did the heating and cooling design for this building using primarily a software package from University of Alabama. Their responsibilities included: size GHP installation, define loop field (depth and spacing), drill test holes to confirm design assumptions, specify grout, purge lines, and start up equipment. The building's construction contractor states that this is only the second commercial-scale GHP installation in Utah (the other is also in Ogden).

The drilling was quite conventional, similar to Fort Polk with clayey, sticky formation. The water table was at about 25', so heat-transfer performance for loops should be good. Bertram tried drilling one hole with air, but there was too much formation water. Loop insertion was driven by a large sinker bar (2.5" dia by ~10' long, which calculates to be 165 lb) with a re-bar stinger on the end, which fit into a PVC socket taped to the bottom of the loop. Loops were manufactured in Canada by "GEO Plast." Bertram drill crew also installed headers after they finished drilling.

The drill site would eventually be the building's parking lot. It had been excavated to about 4' below grade, header trenches dug about 2' below this and back-filled, then 3' of gravel and road-base and finally asphalt laid on top of this surface. Space in the parking lot was limited by overhead lines and by some underground drain lines. EET planned to use methanol/water mixture for circulating fluid (for freeze protection). The drilling contractor files reports on the "average" well to the State.

* * *

JOB/RIG DATA

Job location: American Red Cross bldg. (under construction), 2955 Harrison, Ogden, UT
Formation description: About half-and-half clay with sand seams, water table at ~25', water in sand seams
Survey dates, # of bores observed: Observed 2 holes drilled and completed, 19 June 96
Expected start/finish of job, # of bores: Job started 12 June 96, expected finish by end of June, total 56 holes, (21 holes completed by 19 June)
Borehole characteristics -- Depth: 200' *Diameter:* 5-1/8"
# of bores: 56 planned *Bore/bore spacing:* existing matrix is 13' by 14'
Pipe dia: Loops are made of 1-1/4" nominal (1-3/4" actual OD) stock
Grout type/brand: Baroid "Benseal" *Grout mix:* 25 gal water + 6-8 oz. EZ-Mud Plus per 50 lb. bag
Grout method, specs: Small grout jet-mixer with pump is set alongside hole. Mix grout one bag at a time (6 or 7 total bags per hole) and pump into tremie line (10' threaded sections of PVC pipe). After each bag is mixed and pumped, pull up and lay down ~40' of tremie. Continue until grouted to surface. "Feel" grout level by swabbing with tremie as it's pulled out of hole.
Rig Characteristics -- Type (mud rotary, auger, hammer, etc.): Mud rotary for this job, but has on-board compressor and can air-rotary or hammer drill.
Drive type: Kelly *Axles:* 3 *Rod Length:* 20'/2-7/8" drill pipe
Weight: Door tag says 21,900 kg
Bit type(s): Stepped-blade drag bit; driller estimates 2 bits for entire job Nom. RPM: 100-120
Crew size: Driller + one helper
Ancillary equipment (trucks, backhoes, etc.): Water truck (1600-1800 gal), parts trailer (pulled by rig), pickup -- Rig has Cat 3406 engine, uses 15-20 gal fuel/day for mud drilling, 80-90 for air.

Mud type: Water, quite a bit of native clay in this formation, ~ 1 cup EZ-Mud, some Kwik-Ben (bentonite) as needed
Flow rate/pressure: ~200 gpm @ 110 psi pump pressure
Mud/fluid disposal: Cuttings spread on site, fluid is pumped off to sump and allowed to settle out.
General Comments: Job is running smoothly. Most loops were going in fairly well, but the pre-manufactured loops have a large, sharp-cornered coupling on each leg near the bottom which could present a problem.
Performance observations (all times are "typical") ROP: ~ 200 ft/hr *Time to TD:* < one hour
Loop prep/insert: Loops are pre-assembled, insertion time is < 2 minutes if smooth, 10-15 minutes if it's a problem. They haven't had to pull a loop yet.
Grout time: 15-20 min. *Rig reposition time:* 5-10 min. *Est. loops/day:* 3 - 4 to date
General comments: They are making 3 or 4 holes/day but driller, who is very experienced, estimates that another helper would add one hole/day. Driller spends a lot of time circulating hole clean, which is appropriate for lots of clay and sand, and he pumps a viscous sweep now and then.

III-c. Geo-Loop Inc.

This job was installation of a loop field for a 3-ton GHP system in a new rural home near Yanktown SD. Contractor was Geo-Loop, Inc., and the owner (Jeff Bowen) had designed and built all equipment used in the job. The drill rig, which is a hydraulic top-drive unit mounted on the front bucket arm of a conventional backhoe, is extremely maneuverable and highly innovative. The contractor covers a relatively wide geographical area in Iowa and South Dakota, so drilling conditions are not uniform and loop-field design must be flexible to allow for drilling contingencies. The original loop-field design was 3 holes to 180', but the driller hit gravel and lost circulation on the first hole. Driller changed design to 6 holes to 100'. This required lengthening trenches from the hole locations to the pit. Holes were drilled at an angle of about 5^{O} to increase downhole spacing. No more drilling problems were encountered. This rig routinely drills 180' holes (can probably do 200-250' in the right conditions) and its agility and low environmental impact make it very well suited for its market niche. It is a relatively well-proven piece of equipment, having been used for installation of more than 500 residential and commercial systems in the past 8 years.

* * *

RIG/JOB DATA

Job location: SE South Dakota, (Yanktown) *Drilling Contractor(s)*: Geo-Loop, Inc.
Formation description: Clay/sand/sandstone/gravel
Survey dates, # of bores observed: Sept. 11, 1996; six holes
Expected start/finish of job, # of bores: one day, six holes
Borehole characteristics -- Depth: 100' (planned 180' but lost circulation and gravel at 120') *Diameter*: 4.75" *# of bores*: 6 (planned 3) *Bore/bore spacing*: 10'

Loop dia.: 3/4" HDPE (160 psi) *Grout type/brand*: Baroid "Benseal" w/polymer *Grout mix(gal/bag)*: 23 *Grout pump*: Hydraulic skid with paddle mixer, positive displacement hydraulic cylinder pump, and power reel, all powered by 18 hp Kohler gasoline engine.
Grout method, specs: Insert loop with weight bar and grout hose attached. Lower in hole, no wireline. Mix and pump 2 part grout while pulling grout hose. Very smooth operation, and good grout jobs.
Rig Characteristics --Type (mud rotary, auger, hammer, etc.): Mud rotary, mounted on backhoe's front bucket *Manufacturer*: Contractor (Jeff Bowen) *Drive type*: Hydraulic top-drive *Weight*: 18,000 lb. (incl. tractor); drill head alone weighs about 1800 lb., can be attached/detached to tractor in ~ 5 minutes *# of Axles*: 2 *Bit type(s)*: Drag, carbide cutters *Rod Length/Dia.*: 10'; 2-3/8", Mayhew Jr. connections *Nom. RPM*: 150
Crew size: 2 during this job, normally 3 -- automatic break-out for drill pipe, can trip out of 160' hole in approximately 5 minutes.
Ancillary equipment (trucks, backhoes, etc.): Heavy duty crew-cab pickup pulling water trailer and mud pump; 2-1/2 ton truck carrying Bobcat and supplies, pulling trailer for backhoe rig and grouting skid.
Mud type: Water and EZ-Mud, bentonite for lost circulation and hole problems
Flow rate/pressure: Two centrifugal pumps in series, each powered by 24 hp Onan gas engines. 250 psi max, ~ 250 gpm at 100 psi
Mud/fluid disposal: Mud pit with trenches to each bore (dug before drilling). Mud pump next to pit with hose to rig; cuttings flow to pit. After drilling, top fluids pumped off and pit buried.
General Comments: Very slick operation with innovative equipment. Drill is fast and has adequate power for mid-range GHP drilling. Very maneuverable and clever.
Performance observations (all times are "typical")
ROP: 20 ft/min max *time to TD*: 15 min. *Grout time*: 5 min. (grouter pumps 50 gpm @ 500 psi) *Loop prep/insert*: Loop prep during drilling. Insertion ~ 3 min.
Site Description: Back yard of new rural home. Very tight access and room to move rig.
Rig reposition time: less than 5 minutes *Est. loops/day*: One house/day, incl. headers.
Overall general comments: Fast, clean, and efficient. Can carry enough supplies for ~ 5 homes on 2 trucks. When mobilizing, contractor tries to plan a week's work in an area. Contractor is now taking orders for this drill/tractor rig as a commercial item.

III-d. Danco Enterprises

This visit is different from all others described in the report because it was to a job site at which a horizontal boring machine, rather than a vertical drill rig, was used to emplace the heat pump loop. Because this contractor did not own a vertical drill rig, they must sub-contract conventional drilling, which made vertical bores more expensive than horizontal for them. This is somewhat unusual, since in many parts of the country the reverse cost comparison is true. The GHP installation was a 4-ton heat pump retrofit in a rural home which has a relatively large, level yard with trees, outbuildings, and partially overhanging power lines (obstructions to vertical drilling.) Design for the horizontal loop-field specified 4 loops, each approximately 165' long, with loops a nominal 10' apart and with bores approximately 10' deep.

Several advantages of horizontal boring were illustrated by this job:

Less surface disturbance -- The boring machine is very compact, with a footprint approximately 3' by 8'. Because it pushes the drill head through the ground, without using a drilling fluid to transport cuttings, there is no disposal problem with cuttings or fluids. This makes these units particularly applicable to retrofit installations in homes with mature landscaping, etc. The contractor states that, since acquiring the horizontal boring machine, retrofits have increased from 5% to 50% of his business.

Accessibility -- Because there is no vertical mast, overhead obstructions (trees, power lines, etc.) are not a problem.

Accurate control -- The drilling head contains a unit which transmits an electrical signal. This signal is received at the surface by a hand-held readout which tells the drill's depth and orientation. By rotating the drill string, the driller can control the hole's trajectory. This allows the bores to be properly aligned (both vertically and horizontally). It can also eliminate headers from the loops to the house, because in the proper type of house construction the driller can guide the bore up through the floor of the house directly into the utility room where the heat pump unit is to be installed.

Loop insertion -- In contrast to vertical boring jobs where loop insertion can be difficult, the boring machine steers the drill head to break through the surface at a desired location, and then uses the drill string retraction to pull the GHP loop through the hole. Pulling the loop is much more positive than pushing it, so loop insertion problems are very rare with horizontal machines.

Boring was done with a Vermeer D7x11 machine and went reasonably well, with only minor mechanical problems. Soil was mostly clay, with few cobbles or large rocks, which is nearly ideal for this kind of installation. Holes were guided by a DigiTrak sonde in the drilling head, with a walk-over surface readout.

Equipment convoy comprises: pickup and trailer with boring machine and water tank (approx. 300 gal.); another trailer with backhoe; 14' van with tools, equipment, and loop material.

* * *

JOB/RIG DATA

Job location: 7332 South Charleston Pike; Southeast of Springfield, OH.
Drilling Contractor(s): Danco Enterprises
Formation description: Mostly clay, very minor rocks and cobble
Survey dates, # of bores observed: 21-22 Oct 96, 2 bores
Expected start/finish of job, # of bores: Expect to finish 4 total bores 23 Oct.
Borehole characteristics (this job horizontal boring):
Depth: ~180' long, 10' deep *Diameter*: ~ 3.5 to 4" *# of bores*: 4 *Bore/bore spacing*: 10'
Loop dia: 3/4" nom., 1.06" actual OD *Grout type/brand*: none; slurry from native clay
Grout method, specs: Loop is pulled back through hole by drill string, which rotates and pumps a small amount of water out the head as it retracts.
Rig Characteristics -- Type (mud rotary, auger, hammer, etc.): Horizontal boring
Manufacturer: Vermeer, Model D7x11, 35 hp Kubota diesel engine
Bit type(s): Flat blade, 3.5-4" wide *Rod Length and Dia.*: 6' long by 1.69" body diameter

Crew size: 2 for boring; 1 for loop assembly, etc. *Nom. RPM*: less than 60 rpm
Ancillary equipment (trucks, backhoes, etc.): small backhoe/excavator; water trailer (also carries boring machine); van with drill press, welder, loop material, misc. equipment; at least 1 truck
Mud type: water with Baroid IDP 109 polymer, sometimes other additives
Flow rate/pressure: ~ 5 gpm/500-600 psi
Performance observations (all times are "typical")
ROP: 180' bore in approximately 1 hour
Loop prep/insert: approximately 20 min to lay out and assemble loop; 20 min to pull back once bore is completed.
Site Description: large, relatively flat yard with mature trees and lawn around existing rural home; some trees and outbuildings. If necessary, utility company will mark location of power, gas, phone lines.
Rig reposition time: 30 min. *Est. loops/day*: 3-4
General comments: Because formation was predominately clay, with very little rock or cobble, drilling conditions were near ideal. Weather, in spite of occasional light rain, was also favorable and caused little delay.
Overall general comments: Customer gets a $1500 rebate from the electric utility for heat pump installation. Since buying horizontal-boring machine, retrofits have gone from less than 5% of their business to about 50%.

III-e. Ewbank and Associates

Ewbank contracted to drill 6,000' of hole for loop installation on the west side of an Oklahoma Gas and Electric (OG&E) office/warehouse in northern Oklahoma City. The formation drilled was primarily sandstone with some shale and occasional hard limestone stringers. Based on their own calculations, they elected to drill 15 holes 400' deep on 50' spacing. They used a rig, specifically designed and built by Ewbank for GHP drilling , which has a Chevy chassis with Caterpillar diesel engine, reciprocating pump for drilling fluid or grout, and mast with top-drive. The drill string is 20' joints of 2-3/8" flush-joint drill pipe (2" IF connection) with break-out lugs on each joint. There is a table at the rig floor for making and breaking drill string connections. During this job, drilling was air-rotary with water slug injection, although they also had the capability for mud-rotary and air-hammer. The driller was not required to haul away cuttings or mud from produced water. The rig had a three-man crew: driller, helper, and lead man.

Ewbank normally uses pre-assembled ground loops from Uni-coil, but had not been able to get delivery, and so were making up loops as they drilled. This required fusing two straight tubing runs (1" high-density 5300 or 5400 polyethylene) onto a prefabricated U-tube, then taping two lengths (~12-15' each) of 1" re-bar onto the bottom of the loop for sinker bars.

A typical procedure (sample times-of-day for an arbitrary well) was the following:

TASK	TIME OF DAY	ACTIVITY
1	0920	Spud 3-3/4" hole; driller and helper are handling drill pipe; lead man is making up loop, filling loop with water, setting up grout mixing equipment and supplies. Hole begins producing water at about 12 minutes (60'). Loop assembly takes < 1 hr, doing it in conjunction with other activities. Fill loop with water after assembly.
2	1040	Start mixing grout; 4 ea. 50 lb bags ~ 110 gal of 12 ppg grout
3	1100	Hole is at TD of 400'. Begin pumping grout. Once grout is pumped into hole, loop should be inserted within 45-60 minutes.
4	1105	Finish pumping grout, displace drill pipe with water.
5	1109	Finish displacing drill pipe, begin POOH
6	1128	Finish POOH, pick up cellar box and move rig from over hole
7	1130	Begin loop insertion
8	1132	Loop insertion complete, begin moving rig to next location
9	1157	Rigged up over new location, ready to spud hole.

A later loop installation was considerably more difficult, requiring 12-15 minutes of very hard work pushing the loop into the hole. The hole with difficult loop insertion had produced much more water than the previous ones, but it is not clear that caused insertion problems. All holes would eventually have a cement cap from 5' depth to 15' depth.

* * *

RIG/JOB DATA

1. Rig: 8,000 lb. pull-down, 12,000 pull-back, 1,000 ft-lb. torque, up to 600 rpm, 120 hp to top-drive; 10,000 lb. tugger for tripping; most controls electric over hydraulic, 5 PTO pumps; rig GVW < 26000, A.C. trailer < 10,000 lb. (Rig can be driven and can pull A.C. trailer w/o requirement for Commercial Driver's License)

1a. Rig has a top drive but uses a quill rod. It has a rotary table that grips and turns the break-out lugs for make up and break out. Drill pipe is added and tripped like a kelly rig

1b Rig mud pump has 2 independent hydraulic cylinders, each capable of 15 gpm at ~ 600 psi. One is variable rate and the other is fixed. This pump is also used for grout pumping and water injection during air drilling. (built by Ewbank)

2. On large jobs, Ewbank uses a separate grout truck, with power reeler for grout tremie hose, to follow the rig from hole to hole.
3. Ewbank uses their own test unit to measure conductivity at different locations; conductivity has varied from 0.5 to 2.4 (B/hr-ft-F)
4. Unlike most heat-pump drillers, Ewbank uses software from Trane and IGSHPA to determine heat loads and design/size loop arrays.

5. Oklahoma allows grouped reports on a loop field after project is complete (i.e., not a separate report and survey on each hole)
6. Break-out lugs on drill pipe act as string reamers on each joint (built by Ewbank)
7. Equipment convoy = rig, pickup with A.C. trailer, and pickup with pipe trailer; if they build a vacuum trailer, rig will tow A.C. and pickup will pull vacuum trailer.
8. Ewbank uses a unique grout and loop insertion method. After drilling to TD, with bit still on bottom, they pump grout through the drill pipe and displace DP with water. A float valve in bit sub prevents flow-back while tripping. POOH wet and move rig off hole. Lower the loop into hole with sinker bars attached to loop U-tube. Advantages: allows driller to drill smaller hole (3-3/4") yielding less cuttings and grout; better thermal coupling; grout holds hole open; no wireline damage to loop.

III-f. Mill Pond, Inc.

The location is in a semi-rural development at Port Republic, NJ and the installation was for a relatively small (<2000 sq. ft.) single-family dwelling. This was an open-loop system with a production/injection well pair. The production well would deliver potable water for normal home use and for the heat pump. Production/return well spacing is required by regulation to be at least 50', although there did not seem to be any technical justification for that number. Homes in this area use septic tanks, and the water well spacing/depth requirements are 100' from the septic tank and 100' deep, although this is somewhat negotiable. Water temperature from a typical 100' well is about 55^{O}F and flow rate averages about 50 gpm; using only a small part of that flow is sufficient for approximately 10 tons of refrigeration. Well casing was 4" PVC pipe with 5' of screen at bottom -- state regulations require drilling 8" hole for this assembly (hole must be 4" larger than what's in it). Well casing was grouted to surface; some parts of NJ require cement.

The rig was a small, trailer-mounted, top-drive unit. It was pulled by a 1-ton pickup which was also fitted with a 1000-gal water tank. Another truck carried a smaller water tank and a grout mixer/pump, and pulled a trailer with an air compressor.

Timeline for a typical production well installation was the following:

Time	Activity
1050	Rig arrives on site; level rig, auger hole for mud riser, set mud pan, mix drilling fluid.
1108	Spud production hole.
1248	Reach TD @ 110', circulate drilling fluid while reciprocating pipe.
1252	POOH (keep circulating fluid through fitting on riser to maintain fluid level). With 1 or 2 joints of pipe left in hole, disconnect hose from riser and pump fluid out of mud pan.
1305	RIH with casing; tremie is taped to casing above screen.
1315	Reverse circulate casing with clear water; mud flows onto ground.
1328	Begin mixing and pumping grout while laying down rig.
1340	Continue pumping grout while producing well with air-lift.
1345	Rig ready to move off location; still developing well.

* * *

RIG/JOB DATA

Job location: Port Republic, NJ (Open-loop installation, one pair of wells)
Drilling Contractor(s): Mill Pond, Inc., 279 Main St., Port Republic, NJ 08241
Formation description: Sand, clay, fine gravel
Survey dates, # of bores observed: 7 August 96, 1 bore (production well)
Expected start/finish of job, # of bores: 7 Aug, return well awaiting decision by builder
Borehole characteristics -- Depth: 110' *Diameter*: 7-7/8" *# of bores*: 1 production, 1 return *Bore/bore spacing*: 50' (regulation), 15' is probably OK *Loop dia.*: Casing is 4"
Grout type/brand: Baroid "Benseal" bentonite *Grout pump*: Moineau-type pump
Grout method, specs: Helper mixes one bag at a time in standard mixer and pumps it through tremie with positive-displacement pump
Rig Characteristics -- Type (mud rotary, auger, hammer, etc.): Mud rotary
Manufacturer: Buck Rogers (Olathe, KS) *Drive type*: Top drive *Weight*: < 6000 lb *# of Axles*: 2 *Bit type(s)*: Step-profile drag bit (5 blades) *Crew size*: 3
Rod Length and dia.: 10', 2-3/8" Mayhew Jr. *Nom. RPM*: appears to be ~ 50 rpm
Ancillary equipment (trucks, backhoes, etc.): 2 trucks - one has 1000 gal water tank and pulls rig, the other has additional water tank and trailer with air compressor and grout mixer/pump.
Mud type: "Revert" *Mud/fluid disposal*: Cuttings spread on site; mud reversed out of hole, left on site (water well flow dilutes and disperses it) *General Comments*: Rig uses Mission centrifugal pump (50 psi/200 gpm) for fluid circulation.
Performance observations (all times are "typical") -- ROP: 65 ft/hr *time to TD*: 100 minutes *Loop prep/insert*: 10 minutes to run 5 joints + screen *Grout time*: approximately 20 minutes *Site Description*: Flat, lightly wooded, building lot in semi-rural location
Rig reposition time: NA here, but small *Est. loops/day*: could install well pair in 1 day
General comments: Larger hole size, and possibly smaller rig size, reduce ROP compared to other rigs observed, but necessity for drilling only two holes compensates. Not clear that a more powerful rig would be a significant asset.
Overall general comments: Job could be done more cheaply (and probably more efficiently) with reasonable state regulations.

III-g. Viera Artesian Wells

This contractor primarily does water-well drilling, with some holes used for standing-column heat pumps. Holes are relatively deep (500-1000$^+$ ft), compared to those observed in other locations. Drilling is done almost exclusively with an air-hammer (Viera estimates 5% of holes have too much back-pressure (from water) for hammer, and so must use mud-rotary.) The contractor does drilling only; no pump or loop installation. During this site visit, one hole was completed to 585' and another hole was begun at a different location.

The general procedure was to use a large hammer-drill (~9-1/2") to get down to bedrock (20-150'), run 6-5/8" casing to near bottom, drive the casing in place with a casing-hammer (pneumatic tool like a drill, but with the bit replaced by a mandrel which fits the end of the casing), then go inside the casing with 6" hammer-drill and drill until adequate water-flow is reached. Typical penetration rate in the observed holes appeared to be about 60 ft/hr, but driller said that in other locations it's only 20 ft/hr.

* * *

RIG/JOB DATA

Job location: Andover and North Reading, MA
Drilling Contractor(s): Viera Artesian Wells, 253 Andover Street, Georgetown, MA
Phone (508) 352-8586, Fax (508) 352-8434
Formation description: Overburden; then relatively hard, fractured rock, possibly altered granite
Survey dates, # of bores observed: 26 Aug 96; observed end of one hole, beginning of another
Borehole characteristics -- Depth: first hole 585' *Diameter*: 6" *# of bores*: 1/project
Rig Characteristics Type (mud rotary, auger, hammer, etc.): Mostly air hammer, occasional mud rotary
Manufacturer: REICHdril 625 (1988 model) *Drive type*: Top drive *Crew size*: 2
Weight: 60,000 lb (this is the smaller of Viera's 2 rigs) *# of Axles*: 3
Bit type(s): Solid-head button bits for hammers (about 1000' life), Tungsten-carbide-insert tri-cone for mud drilling. Hammer is Halco Mk66 (made in England). Typical hammer life is 45-50k-ft, replacing piston once in that time. *Nom. RPM*: approximately 15 rpm while hammering
Rod Length and Dia.: 20'; 4-1/2" outside-flush pipe; 3-1/2" API Regular connection; runs pin-up
Ancillary equipment (trucks, backhoes, etc.): Contractor has backhoe available, but not needed at this site. 3-axle truck carries water tank, fuel tank, welder, diaphragm pump, and part of drill pipe.
Mud type: air, with minor water injection *Flow rate/pressure*: compressor is 350 psi, 850 scfm. For mud drilling there is a Wilden (120 psi, 140 gpm) diaphragm pump, or a Gardner-Denver for deeper holes
Mud/fluid disposal: Cuttings stay in back-filled sump; water percolates into ground.
General Comments: Rig uses deck engine for hydraulic power (no PTO from truck engine)
Performance observations (all times are "typical") ROP: 60-80 ft/hr observed, can be 20 ft/hr
Site Description: Both sites observed were for new-home construction. At first location, construction contractor had dug sump; at second, drilling contractor had dug sump in advance of rig arrival.

III-h. Winslow Pump and Well, Inc.

This project comprised drilling 6 boreholes (200' depth) for loop installation to service a large residence, which is in a wooded, rural area being developed with sizable building lots. There was a 400' deep well for potable water on the site; although water began to be encountered at about 20' depth. The GHP contractor drilled the holes, installed the loops, connected them with headers, and provided the penetrations into the house.

The rig was a fairly large, tandem-axle, truck-mounted drill with a crew of three. The contractor's total rolling stock is the drill, a crew-cab truck pulling a trailer with a small backhoe/excavator, and a water tanker (approximately 8000 gallons) delivered to the site by a semi-tractor in advance of the drill and crew.

The bores were drilled in a generally straight line up a gentle slope approximately 50-75' from the house. The procedure was to dig a sump downhill of the lowest borehole and circulate the drilling fluid in it (no separate mud pan), allowing the cuttings to settle out in the sump as much as possible. As the drill moved uphill to the subsequent holes, the trench from the drill to the sump was lengthened and the sump was enlarged as necessary. The suction hose in the sump had a strainer on the end and was suspended off-bottom in a metal-mesh basket hung from the backhoe bucket. After drilling was completed, fluid in the sump was pumped into a nearby gully and the sump was back-filled over the cuttings.

Timeline for a typical installation is the following:

Time	**Activity**
0945	Drill rig arrives.
0955	Unload backhoe, start clearing location and digging sump.
1055	Finish digging sump, fill with water, add a little (~ 1 cup) EZ-Mud, put in suction hose, start circulating.
1102	Spud hole and drill ahead -- drilling down a 20' joint every 1.5-2 minutes.
1125	Hole at TD of 200', circulate briefly and POOH.
1140	Pipe out of hole, RIH with loop, bottom of tremie hose is inside a piece of conduit and is taped to loop.
1142	Loop in place, begin mixing grout in stock tank (approximately 50-60 gal) by circulating it in tank with rig pumps. About 2-1/2 bags (50#) with first batch.
1147	Connect rig pump to tremie and pump grout, mix another batch of about 1-1/2 bags in the same amount of water.
1153	Finish pumping second batch of grout, drop suction line back in sump and displace tremie with water as it's pulled out of hole.
1156	Move to next hole location, use backhoe to lengthen trench to sump.
1215	Spud second hole.
1242	Reach TD on second hole, circulate.
1251	End circulation and POOH.
1300	Begin loop insertion on second hole.

* * *

RIG/JOB DATA

Job location: Bon Air Lane, approximately 8 miles south of La Plata, MD
Drilling Contractor(s): Winslow Pump & Well Inc., PO Box 521, Hollywood, MD 20636
Formation description: Mostly clay, minor sand
Survey dates, # of bores observed: 6 Aug 96, 2 bores observed

Expected start/finish of job, # of bores: 6/7 Aug, 6 bores
Borehole characteristics -- Depth: 200' *Diameter*: 4-1/2" *# of bores*: 6
Bore/bore spacing: 15' apart on a generally straight line
Pipe dia: 2-7/8" *Grout type/brand*: Baroid "Quik-Grout" bentonite *Grout pump*: Rig pump *Grout method, specs*: Insert tremie line with loop, pump grout w/rig pump, pull/pump tremie out after filling annulus from bottom.
Rig Characteristics: Type (mud rotary, auger, hammer, etc.): Mud rotary for this job
Manufacturer: QuikDril 275, I-H S1900 chassis *Drive type*: Top drive (swing arm for pipe handling) *# of Axles*: 3 *Crew size*: 3
Bit type(s): 3-blade, step-profile drag bit *Rod Length*: 20' *Nom. RPM*: ~ 80-100
Ancillary equipment (trucks, backhoes, etc.): crew-cab truck w/backhoe on trailer, water tanker (~8000 gallons) delivered by tractor ahead of rig set-up
Mud type: water with ~ 1 cup EZ-Mud, native clay *Mud/fluid disposal*: Liquid pumped off into a nearby gully, cuttings in dug sump which will be back-filled.
General Comments: Contractor builds loops in shop and delivers to site. This job used Vanguard (McPherson, KS) "Geo-Black" stock, 3/4" nominal size, 1-1/8" actual OD
Performance observations (all times are "typical") ROP: drills 200' hole in ~ 30 minutes
Time to TD: 1/2 hour
Loop prep/insert: pre-made loop, 2-5 minutes insertion *Grout time*: 10 minutes
Site Description: Wooded, rolling hills in rural housing development; drill location is on a sloped, semi-open area which was once a road/path, but which still required clearing some small trees.
Rig reposition time: 20 minutes *Est. loops/day*: up to 10 holes/day in some areas, this job could probably be done in one day with an early start.
General comments: This project has a dug sump, which eliminates use of a mud pan and simplifies cuttings disposal. If the sump has to be enlarged after every wellbore and the trench to the sump lengthened, it isn't clear that this arrangement saves a lot of time.

IV. COST MODEL

After collecting data and observations from the site visits, we faced the task of evaluating the relative importance of possible improvements to the drilling and loop-installation process. To do that, we constructed a cost model spread-sheet (*Microsoft Excel 4.0* format) which accounts for equipment capital cost, equipment operating cost, and time/labor charges. These costs are both those associated with each step of the drilling/installation process for an individual hole and those distributed over the total loop-field project. All these costs are then collected into a total project cost, based on an assumption of the loop-field size. Using this spread-sheet, it is easy to see the effect of changes in any one, or a combination, of the operating conditions.

The spread-sheet is shown, with typical cost values based on the site visits, at the end of this section. A specific case is not used because we agreed to keep each contractor's bid prices, labor rates, and other cost data proprietary. As an example of its use, Figure 2 shows the variation in Total Project Cost (TPC) with various rates of penetration. This curve demonstrates that, if penetration rate is already high (over 100 ft/hr), there is only a minor cost saving by doubling it. If, on the other hand, penetration rate is relatively low (under 30 ft/hr) then doubling ROP can give a significant cost saving.

In Figure 3, the dashed line shows that TPC is relatively insensitive to the capital cost of the rig (this curve based on a rig which can drill 100 feet per hour.) If drilling tends to be slow, then spending more money up front for a faster, more powerful drill rig may provide significant economic benefit. The star symbol represents a $50,000 drill rig which can only drill 50 feet per hour, and the X symbol shows TPC using a $200,000 rig which can drill 200 feet per hour. Clearly these results will vary with the amount of business that the driller enjoys, and with other factors, but all of these can be evaluated with the spread-sheet.

Other effects that can be investigated include:

- Trade-off between hole depth and number of holes.
- Using less expensive materials (bits, drilling fluid, loops, etc.)
- Decreased installation time (loop insertion, headers, rig set-up or re-position, etc.)
- Decreased operating cost (less fuel consumption, smaller crew, longer bit life, etc.)
- Better loop-field design (reduced design time, less loop footage required)
- Increased regulatory requirements (more difficult fluids and cuttings disposal, cemented casing, etc.)

When using this cost model to evaluate loop-field costs, it should also be remembered that minimizing the loop-field installation cost may not yield the same design as a life-cycle calculation for the total system. This is unlikely to happen if a competent designer lays out the loop-field depth and spacing based on life-cycle criteria, but if the drilling contractor also designs the loop-field, the buyer should be sure to understand the basis for the design.

Spread-sheet details:

The spread-sheet is shown with typical values on pages 17-19; once it is set up, any combination of these values can be changed to evaluate the effect on Total Project Cost. If the reader wishes to reproduce the spread-sheet (assuming that MS Excel 4.0 or later is available on a PC), the formulas are given in the Appendix. Alternatively, please contact the first author (John Finger) at e-mail address **jtfinge@sandia.gov** and this file can be sent electronically.

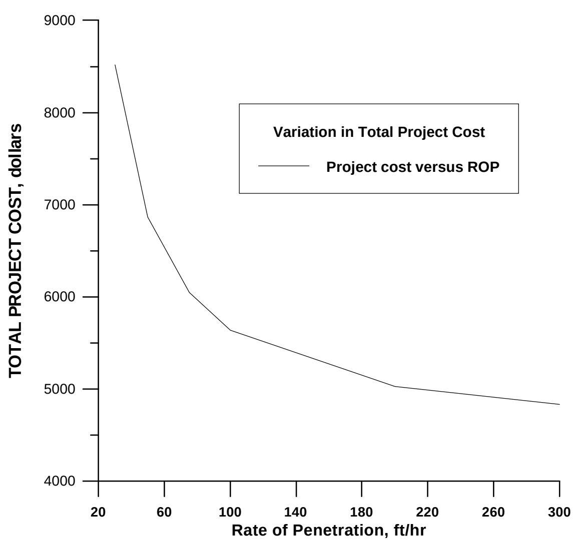

Fig. 2 - Calculations based on a closed-loop project with 6 ea 200' holes

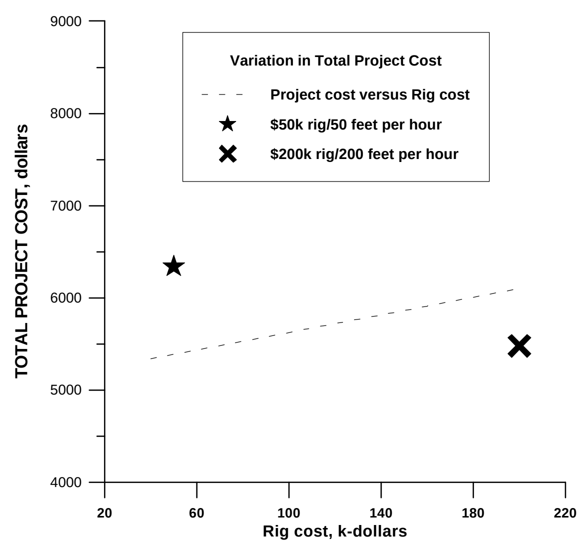

Fig. 3 - Calculations based on a closed-loop project with 6 ea 200' holes

LABOR AND MATERIAL COST ASSUMPTIONS						
LOOP FIELD ASSUMPTIONS						
LABOR		**Rate**		**Driller**	**Helper**	
Wages				$11.00	$9.00	
Workmen's comp		18.0%		$1.98	$1.62	
Medical insurance		$250	man-mo.	$1.42	$1.42	
SUTA		0.034	on first $7k	$0.12	$0.12	
FICA		0.06135		$0.67	$0.55	
Medicare		0.01425		$0.16	$0.13	
Holidays		0.06	12 days/yr	$0.66	$0.54	
Vacation		0.05	2 wk./yr	$0.55	$0.45	
				$16.56	$13.83	
TOTAL LABOR (driller + 2 helpers) HOUR					**$44.22**	
HOLE DESCRIPTION						
Hole depth			200	feet		
Hole diameter			4.25	inches		
Number of boreholes			6			
Rate of penetration			100	ft/hr		
MATERIAL						
Bentonite cost		$0.10	per lb			
EZ Mud						
Water cost		$0.05	per gallon			
Loop mat'l cost		$0.75	per ft (double run)			
1/2" re-bar cost		$0.20	per ft			
Grout cost		$0.50	per gallon			
Grout Interval		0.80	fraction of hole grouted			
Trenching cost		$4.00	per ft			
Header cost		$5.00	per hole			
Bit cost		$300	each			
Bit life		2000	feet			

CAPITAL EQUIPMENT							**Hourly rate**	
							Dollars	**% Total**
DRILL RIG								
Purchase price				$180,000				
	Interest			6.00%				
	Life, months			60				
	Use, hours/week			50				
	Use factor			50%				
	Hourly rate						$32.12	53.30%
Maintenance				Job cost	Frequency			
	Engine							
	- Oil and lube			$60	100	hr.	$0.60	1.00%
	- tune-up			$150	1000	hr.	$0.15	0.25%
	- rebuild			$2,000	5000	hr.	$0.40	0.66%
	Mud pumps							
	- valves and liners			$1,000	2000	hr.	$0.50	0.83%
	- replace			$5,000	10000	hr.	$0.50	0.83%
	Rotary system			$1,000	2000	hr.	$0.50	0.83%
	Drill pipe							
		feet used	200	$2,400	2000	hr.	$1.20	1.99%
		cost/ft	$12					
		life, ft	200000					
	Tires			$2,000	10000	hr.	$0.20	0.33%
		No. tires	10					
		Cost/tire	200					
Fuel								
	gal/hour		3				$3.75	6.22%
	cost/gal		$1.25					
TOTAL HOURLY RATE (drill rig)							**$39.92**	**66.24%**
AUXILIARY EQUIPMENT								
Truck(s)								
Purchase price				$30,000				
	Interest			6.00%				
	Life, months			60				
	Use, hours/week			50				
	Use factor			50%				
	Hourly rate						$5.35	8.88%
Air Compressor								
Purchase price				$70,000				
	Interest			6.00%				
	Life, months			60				
	Use, hours/week			50				
	Use factor			50%				
	Hourly rate						$12.49	20.73%
Maintenance (trucks + AC) = 5% of purchase price/yr							$2.50	4.15%
TOTAL EQUIPMENT HOURLY RATE							**$60.27**	

CALCULATE TOTAL PROJECT COST							
Distributed costs	time, hr	labor cost	mat'l amt.	units	mat'l cost	equipmt	line cost
design loopfield							$1,000.00
locate utilities							$100.00
determine and mark hole locations							$100.00
move rig to location							$500.00
transport mud/cuttings to waste site							
trench (1 man, 20' of trench/hole)	0.5	$6.91	20.00	ft trench	$15.00	$30.13	$312.29
install headers and lay lines in trenches	2	$88.44	20.00	pipe + hdr	$20.00	$120.54	$228.98
back-fill trenches and restore site	1	$44.22				$60.27	$104.49
Total Distributed Cost							**$2,345.76**
Individual hole costs	time, hr	labor cost	mat'l amt	units	mat'l cost	equipmt	line cost
make up loop	0.5	$6.91	210	feet	$157.50		$164.41
reposition rig	0.15	$6.63				$9.04	$15.67
set cellar box and mix mud	0.25	$11.06	25.00	pounds	$2.50	$15.07	$28.62
drill hole	2	$88.44	147.31	H2O+bit	$37.37	$120.54	$246.34
circulate and POOH	0.1	$4.42				$6.03	$10.45
install loop	0.1	$4.42	8.61	gal H2O	$0.43	$6.03	$10.88
pull weight bar OOH	0.1	$4.42				$6.03	$10.45
anchor top of loop	0.1	$4.42	3.00	ft re-bar	$0.60	$6.03	$11.05
grout loop in place	0.4	$17.69	88.39	gal grout	$44.19	$24.11	$85.99
pump excess mud into tank/vacuum truck	0.15	$6.63				$9.04	$15.67
clean and pick up cellar box	0.1	$4.42				$6.03	$10.45
Drilling time/total cost per borehole	**3.45**						**$609.99**
Number of boreholes	6						
Total Project Cost							**$6,005.71**

V. CONCLUSIONS AND RECOMMENDATIONS

Identified cost drivers

During the site visits and other study, several factors in loop-field installation have been identified as major cost drivers:

Rate of penetration*
Environmental/site cleanup*
Loop insertion failures/unsuccessful holes*
Inexact field design*
Equipment (rig, etc.) cost*
Regulatory requirements
Logistics
Great variability in sites and formations

Factors marked with an asterisk (*) are those which we believe may have a technology solution, but any of the other three factors could easily dominate the installation cost.

In considering the possibility of large cost reductions through improved technology, it is well to remember that most GHP drilling is quite similar to water-well drilling and, in fact, a large fraction of GHP contractors either started or have experience in that industry. Water-well drilling is a very mature enterprise and improvements there are far more likely to be incremental (such as increased rate of penetration) than revolutionary; much the same is true for GHP. There are two principal differences from water-well drilling that provide exceptions to this generalization: GHP loop-fields normally require a specific footage of hole to be drilled (as compared to drilling for a water supply) and GHP fields require multiple holes (sometimes a very large number) in a relatively small area. Therefore, any factor that reduces the total footage required for the loop-field installation, or any factor that improves the rig set-up or re-positioning time, can have a significant cost impact.

Possible technology developments

Based on the nature of GHP drilling portrayed above, a number of technology-development projects can be suggested for further research. A partial list of these projects, with brief descriptions, follows:

Replaceable-cutter PDC bits -- Polycrystalline-diamond-compact bits use synthetic diamond cutters to improve ROP in rocks that are harder than those normally drilled for GHP loops. A prototype PDC bit with field-replaceable cutters has been designed by Sandia and will be built and tested in 1997.

Downhole mud hammer -- Air hammers are now used in harder formations, but there are many places where water inflow is too great to allow hole cleaning with only air. A downhole hammer driven by mud circulation could drill with any amount of water entry and could improve ROP in harder rocks.

More mobile, lower impact rigs (coiled tubing) -- Because a loop-field usually has many holes (from a low of 3-4 to as many as hundreds), a drill rig that can move quickly from one location to the next, and which requires a minimum of site clean-up or restoration, is highly desirable. One site visited (Bowen) had a rig which would be considered very small by most standards, but a more conventional machine could not have done that job with the limited access at that location.

Improved grout -- One of the principal factors which determines the footage required for a loop-field is the thermal conductivity of the grout between the loop and the ground. A considerable amount of research has been done on high-conductivity grouts[2] and Sandia has instrumented 18 loops at a GHP installation in a Laboratory building[3]. The instrumented loops at Sandia indicate that a low-performance grout may have conductivity as much as 40% less than a high-conductivity one. Clearly, if high thermal conductivity in the grout can reduce the total footage required to be drilled for the loop-field, that is equivalent to substantial savings in the drilling process itself. Similar instrumentation should be done on loop installations in other soil types.

Grout stability -- In dry soils, much of the liquid used to mix grout leaches away from the borehole, leaving the grout cracked and dry. This degrades its thermal conductivity, with the effects discussed above. There are partial remedies to this problem, such as membranes lining the borehole, but there is an opportunity for significant improvement in this technology.

Loop-field/building-load design software -- Much calculation of building heat loads, and thus loop-field requirements, is empirical and rule-of-thumb. Although several software packages for these tasks exist, it is not clear that these tools are optimum. In particular, in-situ measurements of the ground's thermal conductivity seem to be very useful. This number is typically taken to be some regionally established average, but one of the contractors visited (Ewbank) has equipment to make this measurement at a fairly fine resolution and has found that the "k" value varies by a factor of almost three over the area of one military base.

Drilling workshops -- Sandia convened a drilling workshop in early 1996 to exchange research results and to solicit input from industry on their perception of new technology needs. This is a unique opportunity for a broad view of the GHP industry and a forum for all interested parties to be heard. It is particularly valuable if, as indicated by the Fort Polk experience and by conversation with other contractors, practice and familiarity with GHP drilling leads to greater efficiency and cost savings. A high priority for the GHP program should be continuation of these workshops.

Effect of cost savings

A final recommendation for research or clarification is to explicitly describe the relation between GHP installation cost and GHP market share. It is tempting and reasonable to assume that a classical cost-demand relation exists, and that lowering installation cost would expand GHP demand, but many contractors already have as much work as they can handle and lowering their cost might benefit only them, with little effect seen by the customer and little increase in market share. On the other hand, many GHP contractors have failed, and lower installation costs might have enabled them to compete and survive. There are so many regional differences that affect the success of any business that they cannot all be included in this sort of study, but we can draw some general conclusions about which factors are important in a given scenario. A principal aim of this work has been to provide a tool that GHP contractors can use to evaluate the effect of changing tools or techniques on the cost or price targets that they have identified as essential for their companies' economic viability.

VI. REFERENCES

1. "Closed Loop/Ground-Source Heat Pump Systems – Installation Guide"; Oklahoma State University; distributed by the International Ground Source Heat Pump Association (IGSHPA), 400 Cordell South, Stillwater, OK 74078-8018
2. "Thermal Enhancement of Bentonite Grouts for Vertical GSHP Systems"; C. P. Remund and J. T. Lund; *AES - Vol. 29, Heat Pump and Refrigeration Systems, Design, Analysis, and Applications*; American Society of Mechanical Engineers, 1993
3. "Drilling Innovations for GHPs"; W. N. Sullivan, Proceedings of Conference *Meeting Customer Needs with Heat Pumps*; sponsored by Electric Power Research Institute, St. Louis, MO, December 1995

VII. APPENDIX

The following pages contain the formulas used in the drilling cost model. If you reproduce this (on Excel 4.0 or later), each sheet of the file should have the title at the bottom of its respective page; this will correctly link the sheets as specified by the formulas.

	A	B	C	D	E	F
1	**LABOR AND MATERIAL COST**					
2	**LOOP FIELD ASSUMPTIONS**					
3						
4	**LABOR**		**Rate**		**Driller**	**Helper**
5	Wages				11	9
6	Workmen's comp		0.18		=$C6*E5	=$C6*F5
7	Medical insurance		250	man-mo.	=$C7/(22*8)	=$C7/(22*8)
8	SUTA		0.034	on first $7k	=$C8*7000/2000	=$C8*7000/2000
9	FICA		0.06135		=$C9*E5	=$C9*F5
10	Medicare		0.01425		=$C10*E5	=$C10*F5
11	Holidays		0.06	12 days/yr	=$C11*E5	=$C11*F5
12	Vacation		0.05	2 wks/yr	=$C12*E5	=$C12*F5
13					=SUM(E5:E12)	=SUM(F5:F12)
14						
15	**TOTAL LABOR**					**=E13+2*F13**
16						
17	**HOLE DESCRIPTION**					
18	Hole depth			200	feet	
19	Hole diameter			4.25	inches	
20	Number of boreholes			6		
21	Rate of penetration			100	ft/hr	
22						
23	**MATERIAL**					
24	Bentonite cost		0.1	per lb		
25	EZ Mud					
26	Water cost		0.05	per gallon		
27	Loop mat'l cost		0.75	per ft (double run)		
28	1/2" re bar cost		0.2	per ft		
29	Grout cost		0.5	per gallon		
30	Grout Interval		0.8	fraction of hole grouted		
31	Trenching cost		4	per ft		
32	Header cost		5	per hole		
33	Bit cost		300	each		
34	Bit life		2000	feet		

[F.XLW]LABOR.XLS

	A	B	C	D	E
1	CAPITAL EQUIPMENT				
2					
3	DRILL RIG				
4	Purchase price				180000
5		Interest			0.06
6		Life, months			60
7		Use, hours/week			50
8		Use factor			0.5
9		Hourly rate			
10	Maintenance				Job cost
11		Engine			
12		- Oil and lube			60
13		- tuneup			150
14		- rebuild			2000
15		Mud pumps			
16		- valves and liners			1000
17		- replace			5000
18		Rotary system			1000
19		Drill pipe			
20			feet used	200	=D20*D21
21			cost/ft	12	
22			life, ft	200000	
23		Tires			=D24*D25
24			No. tires	10	
25			Cost/tire	200	
26	Fuel				
27		gal/hour		3	
28		cost/gal		1.25	
29					
30	TOTAL HOURLY RATE (drill rig)				
31					
32	AUXILIARY EQUIPMENT				
33	Truck(s)				
34	Purchase price				30000
35		Interest			0.06
36		Life, months			60
37		Use, hours/week			50
38		Use factor			0.5
39		Hourly rate			
40					
41	Air Compressor				
42	Purchase price				70000
43		Interest			0.06
44		Life, months			60
45		Use, hours/week			50
46		Use factor			0.5
47		Hourly rate			
48	Maintenance (trucks + AC) = 5% of purchase price/yr				
49					
50	TOTAL EQUIPMENT HOURLY RATE				

	F	G	H	I
1			**Hourly rate**	
2			**Dollars**	**% Total**
3				
4				
5				
6				
7				
8				
9			=-12*PMT(E5/12,E6,E4)/52/E7/E8	=H9/$H$50
10	Frequency			
11				
12	100	hrs	=E12/F12	=H12/$H$50
13	1000	hrs	=E13/F13	=H13/$H$50
14	5000	hrs	=E14/F14	=H14/$H$50
15				
16	2000	hrs	=E16/F16	=H16/$H$50
17	10000	hrs	=E17/F17	=H17/$H$50
18	2000	hrs	=E18/F18	=H18/$H$50
19				
20	=D22/[F.XLW]LABOR.XLS!$D$21	hrs	=E20/F20	=H20/$H$50
21				
22				
23	10000	hrs	=E23/F23	=H23/$H$50
24				
25				
26				
27			=D27*D28	=H27/$H$50
28				
29				
30			**=SUM(H9:H27)**	**=H30/$H$50**
31				
32				
33				
34				
35				
36				
37				
38				
39			=-12*PMT(E35/12,E36,E34)/52/E37/E38	=H39/$H$50
40				
41				
42				
43				
44				
45				
46				
47			=-12*PMT(E43/12,E44,E42)/52/E45/E46	=H47/$H$50
48			=(E34+E42)*0.05/2000	=H48/$H$50
49				
50			**=SUM(H30:H48)**	

	A	B	C	D	E	F
1	CALCULATE TOTAL PROJECT COST					
2						
3	Distributed costs				time, hours	labor cost
4						
5	design wellfield					
6	locate utilities					
7	determine and mark hole locations					
8	move rig to location					
9	transport mud/cuttings to waste site					
10	trench (1 man, 20' of trench/hole)				0.5	=E10*[F.XLW]LABOR.XLS!$F$13
11	install headers and lay lines in trenches				2	=E11*[F.XLW]LABOR.XLS!$F$15
12	back-fill trenches and restore site				1	=E12*[F.XLW]LABOR.XLS!$F$15
13						
14	Total Distributed Cost					
15						
16	Individual hole costs				time, hours	labor cost
17						
18	make up loop				0.5	=E18*[F.XLW]LABOR.XLS!$F$13
19						
20	reposition rig				0.15	=E20*[F.XLW]LABOR.XLS!$F$15
21	set cellar box and mix mud				0.25	=E21*[F.XLW]LABOR.XLS!$F$15
22	drill hole				=[F.XLW]LABOR.XLS!$D$18/[F.XLW]LABOR.XLS!D	=E22*[F.XLW]LABOR.XLS!$F$15
23	circulate and POOH				0.1	=E23*[F.XLW]LABOR.XLS!$F$15
24	install loop				0.1	=E24*[F.XLW]LABOR.XLS!$F$15
25	pull weight bar OOH				0.1	=E25*[F.XLW]LABOR.XLS!$F$15
26	anchor top of loop				0.1	=E26*[F.XLW]LABOR.XLS!$F$15
27	grout loop in place				0.4	=E27*[F.XLW]LABOR.XLS!$F$15
28	pump excess mud into tank/vacuum truck				0.15	=E28*[F.XLW]LABOR.XLS!$F$15
29	clean and pick up cellar box				0.1	=E29*[F.XLW]LABOR.XLS!$F$15
30						
31	Drilling time/total cost per borehole				=SUM(E20:E29)	
32						
33	Number of boreholes				=[F.XLW]LABOR.XLS!$D$20	
34						
35	Total Project Cost					

	G	H	I
1			
2			
3	mat'l amt	units	material cost
4			
5			
6			
7			
8			
9			
10	20	ft trench	=G10*[F.XLW]LABOR.XLS!$C$27
11	20	pipe + hdr	=G10*[F.XLW]LABOR.XLS!$C$27+[F.XLW]LABOR.XLS!$C$32
12			
13			
14			
15			
16	mat'l amt	units	mat'l cost
17			
18	=[F.XLW]LABOR.XLS!$D$18+10	feet	=G18*[F.XLW]LABOR.XLS!$C$27
19			
20			
21	25	pounds	=G21*[F.XLW]LABOR.XLS!$C$24
22	=[F.XLW]LABOR.XLS!$D$19^2*0.785*[F.XLW]LABOR.XLS!$D$18*12/231	H2O+bit	=G22*[F.XLW]LABOR.XLS!$C$26+[F.XLW]LABOR.XLS!$C$33*[F.XLW]LABOR.XLS!$D$18/[F.XLW]LABOR.XLS!$
23			
24	=G18*0 041	gal H2O	=G24*[F.XLW]LABOR.XLS!$C$26
25			
26	3	ft re-bar	=G26*[F.XLW]LABOR.XLS!$C$28
27	=G22*[F XLW]LABOR XLS!$C$30*0.75	gal grout	=G27*[F.XLW]LABOR.XLS!$C$29
28			
29			
30			
31			
32			
33			
34			
35			

	J	K
1		
2		
3	equipment	line cost
4		
5		1000
6		100
7		100
8		500
9		
10	=E10*[F.XLW]CAPITAL.XLS!$H$50	=(F10+I10+J10)*[F.XLW]LABOR.XLS!$D$20
11	=E11*[F.XLW]CAPITAL.XLS!$H$50	=F11+I11+J11
12	=E12*[F.XLW]CAPITAL.XLS!$H$50	=F12+I12+J12
13		
14		=SUM(K5:K12)
15		
16	equipmt	line cost
17		
18		=F18+I18+J18
19		
20	=E20*[F.XLW]CAPITAL.XLS!$H$50	=F20+I20+J20
21	=E21*[F.XLW]CAPITAL.XLS!$H$50	=F21+I21+J21
22	=E22*[F.XLW]CAPITAL.XLS!$H$50	=F22+I22+J22
23	=E23*[F.XLW]CAPITAL.XLS!$H$50	=F23+I23+J23
24	=E24*[F.XLW]CAPITAL.XLS!$H$50	=F24+I24+J24
25	=E25*[F.XLW]CAPITAL.XLS!$H$50	=F25+I25+J25
26	=E26*[F.XLW]CAPITAL.XLS!$H$50	=F26+I26+J26
27	=E27*[F.XLW]CAPITAL.XLS!$H$50	=F27+I27+J27
28	=E28*[F.XLW]CAPITAL.XLS!$H$50	=F28+I28+J28
29	=E29*[F.XLW]CAPITAL.XLS!$H$50	=F29+I29+J29
30		
31		=SUM(K18:K29)
32		
33		
34		
35		=K14+E33*K31

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